# On the Performance Analysis of Different Link to Path Restoration Schemes for All-Optical Networks

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*Abstract*— In this paper we compare the performance of three different restoration schemes for all-optical networks (link, subpath and path) upon a single link failure considering physical layer impairments. In addition, we propose two strategies for link or subpath restoration. Although the strategies based on subpath restoration present a better performance when compared to the strategies based on link restoration, the path restoration scheme far outperforms these other schemes. From the results, there is an indication that the path restoration is the best reactive scheme for all-optical network without wavelength conversion.

*Keywords*— All-optical networks, physical layer impairments, restoration, single link failure.

## I. INTRODUCTION

All-optical networks have been considered as the most reliable and cost-effective solution to obtain high transmission rates for long-haul distances with a low relative cost. In these networks, the signal remains in the optical domain between the edge nodes without optical-electrical-optical conversion [1]. One of the major challenges in all-optical networks is to ensure the quality of transmission of the signal from the source to the destination node [2], [3]. Therefore, the signal degradation imposed by physical layer effects [4]–[6] should be considered by the control plane during the network operation, including the routing and wavelength assignment (RWA) process both for primary and backup lightpaths.

Since an optical network carries a huge amount of data, a failure, such as an human error, an equipment failure or a natural disaster [2], [7], can imply in interruptions of some telecommunications services, leading to a technical and/or economic disorder. In order to avoid this, optical networks have to be resilient to failures [8].

There are two main survivability schemes for optical networks: protection and restoration. The former reserves backup lightpaths in advance to guarantee resources in the case of a failure, whereas the latter mechanism aims to react after the failure, *i.e.* an algorithm search for backup resources in real time after the occurrence of a failure [2], [7]–[10]. A protection scheme can recover a connection faster than a restoration

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scheme. On the other hand, the restoration scheme is more attractive because it does not need to reserve resources in advance [10]–[12]. In the restoration case, if there is no route available to reconnect a previous active lightpath, then this connection is lost.

Wang *et. al* [12] presented a classification for the restoration schemes:

- Link: the restoration algorithm tries to find a route between the adjacent nodes of the link with failure.
- Path: the restoration algorithm tries to find a route between the source node and the destination node of each active lightpath of the link with failure.
- Subpath: the restoration algorithm tries to find a route between the predecessor node before the failure and the destination node of each active lightpath of the link with failure.

In this paper, we perform a comparative analysis between link, subpath and path restoration, considering a single link failure scenario and no wavelength conversion capabilities. One should remember that the infrastructure of most of the current optical networks can not perform wavelength conversion. We used the shortest path algorithm to search the backup route and the first fit policy to assign the backup wavelength. An alternative lightpath is selected for restoration if the physical layer impairments do not degrade the signal beyond a pre-defined level. We considered the following physical layer effects in our analysis: the effect of gain saturation and amplified spontaneous emission (ASE) noise depletion in amplifiers, coherent crosstalk in optical switches and polarization mode dispersion (PMD) in optical fibers.

Furthermore, we propose in this paper two novel strategies to improve the performance of the link and subpath restoration schemes, one based on the connectivity of the nodes and the other in an exhaustive search.

The remainder of the paper is organized as follows. In Section II we present some previous works that contributed for the solution of the survivability problem considering reactive schemes. In Section III, we present the novel strategies to improve the performance of the link restoration and subpath restoration schemes. In Section IV, we describe the simulation setup, the optical signal-to-noise ratio (OSNR) model and the parameters for the physical layer effects. In Section V, we show the performance analysis of the link, subpath and path restoration schemes. In Section VI, we give our conclusions.

## II. LITERATURE REVIEW OF RESTORATION SCHEMES

The survivability problem in optical networks has been investigated since the last decade of the 20th century [13], [14]. Ramamurthy *et. al* [8] proposed to analyze the survivability in optical networks considering different strategies, such as protection and restoration. Pavani *et. al* [15] proposed a single fault-tolerant dynamic RWA algorithm based on the ant colony optimization (ACO) to provide lightpaths in an optical network. Wang *et. al* [12] performed a comparative study among the path, link and subpath restoration schemes. However, they did not consider the physical layer impairments and considered that all nodes of the network present wavelength conversion, which is not realistic for most of the networks.

The impairments imposed to the signal by the physical layer were considered in the survivability problems by: Rosa *et al.* [16], in which they considered the ASE and PMD effects; Georgakilas *et al.* [17], in which they considered the ASE, cross-phase modulation and FWM effects; and Adami *et al.* [18], in which they considered the inter-symbol interference and ASE effects. These previous works considered physical layer impairments, but none of them compared different link to path restoration schemes.

## III. LINK, SUBPATH AND PATH RESTORATION SCHEMES

In the next subsections we present the link and subpath restoration classical algorithms, as well the novel strategies.

### A. Link restoration

The main characteristic of this restoration strategy is that the source node and destination node of the connection are not notified about the failure. Only the adjacent nodes of the link with failure participate in the reestablishment of the disrupted calls. Furthermore, since we assume no wavelength conversion, the wavelength continuity of the lightpaths has to be ensured, *i.e.* the wavelengths used by the alternative lightpaths should be the same of the primary disrupted lightpaths [11], [12].

Algorithm 1 presents the pseudocode of the classical link restoration scheme. For each link $L$ belonging to the topology $T$, composed by $Nodes$ and $Links$, we identify the calls that pass through it and then we simulate a failure. For each disrupted call, a path segment that bypasses the link with failure is searched. This operation occurs from the node that precedes the link with failure until the node that succeeds the failure. In the sequence, the possibility of wavelength continuity is evaluated. In the line 8 occurs the composition of the backup lightpath as follows: the segment of the primary path located before the failure is enchained with the new segment of the path that contours the link with failure and with the segment of the primary path, located after the failure. Finally, the QoT of the alternative lightpath is evaluated. If it is acceptable, then the call is recovered.

### B. Link restoration considering the most connected node

We propose here a variation of the link restoration scheme, which aims to contour the link with failure from the most

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**Algorithm 1:** Pseudocode of the classical link restoration.

```
1  for each L ∈ T(Nodes, Links) do
2      Identify the calls ∈ L;
3      Simulate the link L failure;
4      for each call ∈ L do
5          Search for a route segment, with the maximum
             OSNR, that contours the failure;
6          Evaluate the availability of wavelength continuity;
7          Compose the complete alternative lightpath;
8          Evaluate the physical layer impairments;
9      end for
10 end for
```

connected node among the nodes that belong to the segment of primary lightpath located before the failure.

Algorithm 2 shows the pseudocode for our proposal for restoration considering the most connected node. The $maxnode$ function is responsible for the identification of the most connected node of the primary path located before the link with failure.

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**Algorithm 2:** Pseudocode of the Link restoration considering the most connected node.

```
1  for each L ∈ T(Nodes, Links) do
2      Identify the calls ∈ L;
3      Simulate the link L failure;
4      for each call ∈ L do
5          Identify the maxnode of the primary route;
6          Search for a route segment, with the maximum
             OSNR, that contours the failure;
7          Evaluate the availability of wavelength continuity;
8          Compose the complete alternative lightpath;
9          Evaluate the physical layer impairments;
10     end for
11 end for
```

### C. Link restoration limited by the most connected node degree

In this other proposal, called also as exhaustive link restoration, the call restablishment occurs from the most connected node and the number of attempts is equal to the degree of this node minus two. This subtraction is done to avoid a loop situations: the two links that compose the primary lighpath are not considered in the restoration process. Thereby, the attempt to find a segment of backup route is performed for each link attached to the most connected node. For example, if the most connected node has degree equal to 5, the number of attempts to restore is 3.

Algorithm 3 shows the exhaustive link restoration process. For each disrupted call, it is identified the most connected node located before the failure. The number of attempts $qty_{(retry)}$ to restore a disrupted call is limited to the most connected node degree given by the $degree_{(maxnode)}$ function. A route segment that bypasses the failure is searched and the

wavelength and the availability is evaluated. The alternative lightpath is composed by the segment of the primary path, located before the failure, enchained with the new segment of the path that contours the link with failure and with the segment of the primary path, located after the failure. The QoT of the alternative lightpath is evaluated. If it is acceptable, then the call is recovered.

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**Algorithm 3:** Pseudocode of the link restoration limited by the most connected node degree.

1 **for** *each* $L \in T(Nodes, Links)$ **do**
2      Identify the calls $\in$ L;
3      Simulate the link $L$ failure;
4      **for** *each call* $\in$ *L* **do**
5          Identify the $maxnode$ of the primary route;
6          **while** $qty_{(retry)} < degree_{(maxnode)} - 2$ **do**
7              Search for a route segment, with the maximum OSNR, that contours the failure;
8              Evaluate the availability of wavelength continuity;
9              Compose the complete alternative lightpath;
10              Evaluate the physical layer impairments;
11              **if** *(success)* **then**
12                  Restore the call;
13                  Go to next call;
14              **else**
15                  Increment $qty_{(retry)}$;
16              **end if**
17          **end while**
18      **end for**
19 **end for**

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### D. Classical subpath restoration

This approach can be considered as a hybrid between the link restoration (because the node that precedes the failure participates of the recovery process) and the path restoration (because the destination node of the call participates of the reestablishment of the lightpaths). In this strategy, the search for a backup route occurs from the node before the link with failure until the destination node.

This approach is similar to the one presented in Algorithm 1. The difference relies in the line 5, in which the new segment of backup lighpath is searched from the node located before the link with failure to the destination node of the call.

### E. Subpath restoration considering the most connected node

In this proposal, the restoration process begins at the most connected node of the primary path located before the failure. The backup lightpath is composed by two parts: *i)* the segment of primary route located from the source node to the most connected node before the link with failure and *ii)* the new segment of route. The full backup lightpath must be established in the same wavelength used by the primary lightpath.

This algorithm is similar to the Algorithm 2 which presents the strategy for link restoration considering the most connected node. The difference relies in the line 6, in which the destination node of the new segment of route is no longer the node that succeeds the link with failure, but the call destination node.

### F. Subpath restoration limited by the most connected node degree

This strategy, also called in this paper as exhaustive subpath restoration, attempts to find a backup route on exhaustive way *i.e.*, the search for the backup route is performed from each link attached to the most connected node located before the failed link to the call destination node.

### G. Path restoration

The path restoration scheme tries to find an alternative route from the source node until the destination node of the call. In this scheme, the wavelength continuity is not required.

Algorithm 4 shows the path restoration process. When a link failure occurs, all the affected calls are identified and in the sequence, their resources are set free. An attempt to find an alternative route and an available wavelength is done. Finally, the impairments of the candidate lightpath are evaluated.

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**Algorithm 4:** Pseudocode of the path restoration.

1 **for** *each* $L \in T(Nodes, Links)$ **do**
2      Identify the calls $\in$ L;
3      **for** *each call* $\in$ L **do**
4          Set free the occupied lightpaths $\in$ L;
5      **end for**
6      Simulate the link $L$ failure;
7      **for** *each call* $\in$ L **do**
8          Search for an alternative route that presents the maximum OSNR;
9          Evaluate the availability of wavelength;
10          Evaluate the physical layer impairments;
11      **end for**
12 **end for**

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## IV. SETUP SIMULATION

For the performance evaluation of the strategies presented in Sections III-A to III-G we used the simulation parameters presented in Table I. The simulations are performed by the SIMTON simulator [19]. The topology used in our simulations is shown in Figure 1. We used 20 wavelengths per link. For each restoration scheme, we performed 30 simulations and we evaluated the unsuccess ratio of the failure recovery (URFR) by:

$$URFR_{(\%)} = 1 - \left( \frac{qty_{(recovered)}}{qty_{(affected)}} \right) \times 100, \qquad (1)$$

in which, $qty_{(recovered)}$ indicates the number of disrupted calls that achieves success on the restoration process and $qty_{(affected)}$ represents the number of calls that uses the link with failure.

For the simulations of a single link failure, we used the following methodology proposed by Freitas *et al.* [20], [21]. This methodology has five steps: (1) initially, we analyze the network occupation in order to identify the point at which the topology stabilizes regarding the average usage of wavelengths
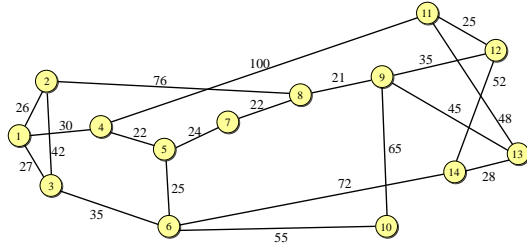
Fig. 1: Topology used in the simulations. The numbers in the links indicate the link lengths in km.

per link, *i.e.* we check how many calls are necessary for the network to achieve the steady state. This investigation is important because the faults should be simulated considering the steady state condition of the network; (2) the steady state is stored in order to perform the simulations of failures on a realistic scenario; (3) given the stored state of the network, a link of the topology is removed, simulating the disruption of an optical fiber; (4) the restoration algorithm (link, path or subpath) tries to reestablish the calls that pass through the failed link. A call is considered recovered when there is an available alternative lighpath and its QoT is acceptable; (5) The steps 3 and 4 are repeated for each link of the topology.

We utilized an analytical model based on the OSNR degradation [3] to take into account the effect of gain saturation and amplified spontaneous emission (ASE) noise depletion in amplifiers, coherent crosstalk in optical switches and PMD in optical fibers.

We used the shortest path algorithm and the first fit policy for routing and wavelength assignment, respectively. For the considered restoration strategies we assumed that the wavelength used in the restored lightpath is the same used by the disrupted lightpath.

TABLE I: Default simulation parameters.

| Parameter | Value | Definition |
|---|---|---|
| $P_{sat}$ | 26 dBm | Amplifier output saturation power. |
| $OSNR_{in}$ | 40 dB | Input optical signal-to-noise ratio. |
| $OSNR_{QoS}$ | 23 dB | Optical signal-to-noise ratio for QoS criterion. |
| $B$ | 40 Gbps | Transmission bit rate. |
| $B_o$ | 100 GHz | Optical filter bandwidth. |
| $\Delta f$ | 100 GHz | Channel spacing. |
| $\lambda_i$ | 1529.56 nm | The lower wavelength of the grid. |
| $\lambda_0$ | 1557 nm | Zero dispersion wavelength. |
| $\alpha$ | 0.2 dB/km | Fiber loss coefficient. |
| $L_{Mux}$ | 2 dB | Multiplexer loss. |
| $L_{Demux}$ | 2 dB | Demultiplexer loss. |
| $L_{Switch}$ | 2 dB | Optical switch loss. |
| $\delta$ | 10% | Maximum pulse broadening. |
| $W$ | 20 | Number of wavelengths per link. |
| $F_0$ (NF) | 3.162 (5 dB) | Amplifier noise factor (Noise figure). |

## V. RESULTS

Figure 2 shows the performance in terms of URFR as a function of the network load for all six restoration algorithms investigated in this paper: *i)* classical link (Link), *ii)* most connected link (MCLink), *iii)* exhaustive link (ELink), *iv)* classical subpath (Subpath), *v)* most connected subpath (MCSub), *vi)* exhaustive subpath (ESub), and also the path restoration based on OSNR proposed by Freitas *et. al* [20].

The classical link restoration algorithm presents the worst performance. This strategy recovers less than 4% of the disrupted lightpaths for a network load of 60 erlangs. The most connected link and exhaustive link restoration schemes show a slightly higher restoration success than the classical link restoration. In the investigated scenario it was possible to restore about 6% of the interrupted calls, using these strategies.

The classical subpath restoration scheme presents a significant gain in comparison to the previous strategies based on link restoration. In the investigated scenarios, the URFR decreases from 93% (for exhaustive link restoration) to 86% (for classical subpath restoration). The strategies based on subpath restoration achieve a better performance than the restoration strategies based on the link restoration.

By applying the most connected subpath restoration algorithm, one could reduce the URFR to 76%, achieving a gain of 17 and 10 percentage points, respectively, over the exhaustive link restoration and classical subpath restoration.

The exhaustive subpath restoration strategy presents the best performance among the three proposals based on the link restoration and the three proposals based on subpath restoration. In the investigated scenario the URFR of this approach achieved 71%.

It is important to highlight that the strategies which consider both the most connected node and the exhaustive restoration increase the computational complexity of the lighpath search process.

Finally, it is observed the superiority of the path restoration over the six other strategies. This difference of performance is justified by the fact that in the path restoration scheme has more flexibility to find new routes in comparison with the other strategies.

The strategies based on most connected link, proposed in this paper, promoted some gain of performace in comparison with classicals link and subpath restoration schemes. Nevertheless, the resulting URFRs of these schemes are still worse than the URFR that could be achieved by the path restoration strategy.

Figure 3 shows the boxplot of the URFR for each one of the seven investigated restorarion schemes. To compose the graphic we considered the URFR returned by 30 independent simulations for each restoration algorithm and a network load of 60 erlangs. The results indicate a small variance among the URFRs obtained which ensure their reliability and also confirm that the exhaustive subpath restoration strategy and the path restoration are the best survivability reactives schemes.

## VI. CONCLUSIONS

In this paper we present a comparative study among the three main restoration schemes for an optical network (link,
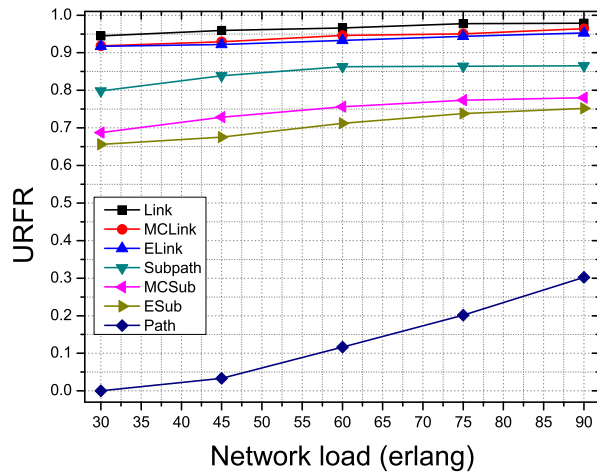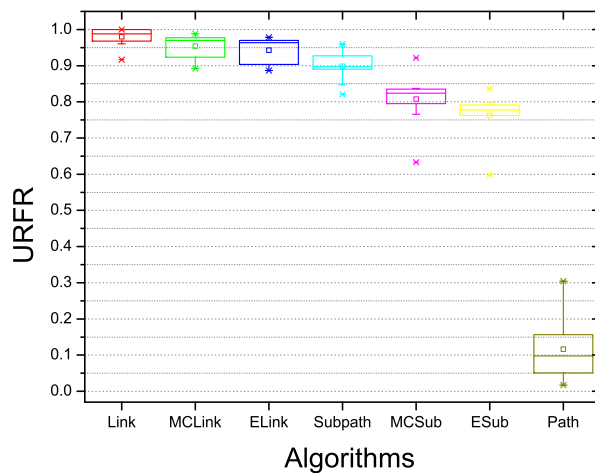
Fig. 2: URFR as a function of the network load.



Fig. 3: Boxplot chart of the URFR for all considered restoration schemes for 60 erlangs.

subpath and path). Moreover, we propose two strategies to increase the performance of the link and subpath restoration schemes. The first proposal is based on the most connected node and the second is based on the exhaustive attempts to find a backup lightpath. The results indicate the superiority of the path restoration scheme over the strategies based on link and subpath restoration.

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